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Environment driven consumer EC model incorporating complexities of consumer body dynamics

Sahibzada Muhammad Ali[1], Bilal Khan[1], Geev Mokryani[2] ✉, Chaudhry Arshad Mehmood[1], Muhammad Jawad[3], Umar Farid[1]

[1]Department of Electrical & Computer Engineering, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, Pakistan
[2]School of Electrical Engineering and Computer Science, University of Bradford, Bradford, UK
[3]Department of Electrical Engineering, COMSATS University Islamabad, Lahore Campus, Lahore, Pakistan
✉ *E-mail: g.mokryani@bradford.ac.uk*

Abstract: Energy consumption (EC) of consumers primarily depends on comfort level (CL) affirmed by brain sensations of the central nervous system. Environmental parameters such as surroundings, relative humidity, air temperature, solar irradiance, air pressure, and cloud cover directly influence consumer body temperature that in return affect blood dynamics perturbing brain comfort sensations. This CL (either in summer, winter, autumn, or spring season) is a function of external environment and internal body variations that force a consumer toward EC. To develop a new concept of consumer's EC, first the authors described environment parameters in detail with relation to surroundings and EC. Considering this, they tabulated a generic relation of consumer's CL with EC and environment temperature. Second, to build an inter-related bond between the environmental effects on consumer body dynamics, they analysed theoretically and mathematically above mutual relations between medical and environmental sciences. Finally, they present their conceptual EC model based on a closed-loop feedback system. This model is a complex non-linear adaptive system with environmental and surrounding parameters as input to the system resulting in an optimised EC, considering consumer CL as a key parameter for the system.

1 Introduction

With increased energy profiles of consumers (energy-consuming humans) in recent years, there is a clear need to design intelligent, advanced, and automated energy consumption systems (ECSs) for the future. The consumer empowerment and consumer comfort (satisfaction) are the integral entities of ECSs. Environment and surrounding parameters are the driving force in modelling, analysis, and forecasting consumer behaviour and psychology toward energy consumption (EC). The aforementioned factors are stimulated by consumer's internal body dynamics. Comfort demand of consumer body is fulfilled through a compelling central nervous brain sensational force stimulated by blood signals from various body parts. Considering above, there is a very strong bond between Earth's atmosphere, environment, and surroundings, consumer body dynamics (CBD), and EC [1]. To further support this claim, consider a consumer psychology example of John Locke in his essay saying that: '*A person places one hand in a basin of warm water and other in a basin of cool water. After a short time, both hands are placed in the third basin of water, which is at an intermediate temperature. The hand previously in warm water feels cool and the hand previously in cool water feels warm even though they are at the same temperature*' [2].

Thus, consumer psychology is a highly complex and stochastic system, affected by external surrounding and environment. Non-uniform and transient external conditions are exposed to consumers during random movement from 'outdoor-to-indoor' and 'indoor-to-outdoor' spaces. CBD parameters such as: (a) blood pressure, (b) stress, (c) haemoglobin level, and (d) vasomotion actions show dynamic responses to central nervous system (CNS). Brain sensation (BS) signals are transmitted to achieve optimised comfort level ($CL_{,\,opt}$). CLs of consumers vary probabilistically within such random environmental movements. Consumers 'switch ON or OFF' the electric devices, namely thermostat, air conditioning (high-voltage AC system), and ventilating, lighting, and heating system. With adaptation to comfort environment, the CBD settles down to steady state.

Consumers thermal comfort is defined by Hassan in 1991 as: '*A state in which there are no driving impulses to correct the environment by behaviour*' [3]. Moreover, it is more satisfied and contented state of mind with the thermal environment. Environmental parameters, namely air pressure (AP), relative humidity (RH), air temperature (AT), air speed (AS), solar irradiance (SI), cloud cover (CC), precipitation (P), and dew point (DP) strongly drift the parameters of neighbouring surroundings. Surrounding atmospheric parameters, for example, carbon dioxide (CO_2) emissions (air pollution), forestry, and consumer location (CLo) strongly influence environmental parameters. Consumer's psychological factors such as consumer physical activity (exercise), economic, and financial status, and clothing stimulates the thermoregulation system. To model a relation between CL and EC is a challenging task. As CL varies from 'consumer-to-consumer' with drifting environment parameters, the parameter design for an accurate, predictable, robust, and intelligent complex adaptive dynamical ECS is highly challenging complex work.

The intimate relation between environmental parameters, CBD, and CL require high attention. As energy demand (ED) of consumers is massively increasing, the electrical utilities are facing continuous and alarming problems such as (a) drastic load increase, (b) demand–supply mismatch, (c) energy forecast errors between past histories and present consumption, (d) consumer's low participation in demand–response programmes for shaping energy profiles, and (e) lack of consumer's empowerment and consumer psychology penetration with ECSs [4].

Moreover, to the best of our knowledge, current ECS's monitoring, measurement, protection, management, and control are unable to develop a technical relation and understanding between environment parameter, CBD, CL, and EC. Furthermore, regression analysis of weather and climatic drifts with EC are modelled vaguely, in general terms and consequently the desired outputs are uncertain and diverse [5]. This is because of an inter-related missing CBD and CL parameters in modelling with external environmental inputs. To develop above non-linear function is a goal-directed model. Instead of routine correlation and regression analysis, we develop a closed-loop feedback system with environmental parameters as input and a central controller to maintain an optimum CL during transient-state and steady-state conditions of the consumer body.

One thread of the research body discussed the alarming impacts of environmental conditions on consumer CL and EC. Various generic state-of-the-art works on environmental effects on EC and environment penetrations on consumer comfort exists in the literature. For example, Taleghani [6] presented outdoor thermal comfort through various heat palliation schemes, while Asadi *et al.* [1] presented the indoor environmental quality (IEQ) and EC in the building based on resident behaviour. Moreover, the impact of outside temperature on EC and generation for high-performance buildings was analysed by Cruz *et al.* [4]. In this paper, the continuous real-time data obtained from four high-performance research buildings and finally presented the results from a set of correlations between several variables, namely: (a) outside temperature, (b) heat index, (c) electricity consumption, and (d) generation of solar energy. The authors concluded that there was no relation between outdoor temperature and electricity use in buildings. Furthermore, they discovered the effect of increased outdoor temperature on solar energy generation with decreased efficiency. Ghani *et al.* in [7] presented thermo-physiological models and their applications. The authors explained the existing thermoregulation standards for the entire body and other secluded parts of the body. They discussed various thermal models and their applications.

The outside air-conditioned area thermal comfort was presented by Ghani *et al.* [7] using on-site observers works, on-spot climatic measurements, and computational fluid dynamics. The authors designed five special thermal comfort catalogues, namely: (a) wet-bulb globe temperature index, (b) humidex, (c) mean comfort vote, (d) cooling power index, and (e) discomfort index for thermal comfort measurement. Furthermore, Wang *et al.* analysed the passive house buildings IEQ and energy performances in [8]. They analysed the indoor quality of air and thermal comfort both experimentally and numerically. From the measurement and simulation results, they concluded that it was potential to understand energy efficacy and the favourable interior environment in passive buildings at similar periods. Auffhammer and Mansur in [9] presented climatic impacts measurement on EC, while Ning *et al.* discussed numerically the heat transference rate among a sleeping consumer body and surrounding environment [10].

Rupp *et al.* discussed human thermal comfort in the built environment [11]. They examined various standards including indoor experiments in a semi-controlled and fully controlled environment, field studies inside residential buildings, and educational offices, outdoor, and semi-outdoor field studies. Auffhammer and Mansur in [9] elaborated models of residential ED with temperature. They observed that ED projections were based on temperature response functions. Moreover, Chandramowli and Felder in [12] discussed the global warming and urban heat island impacts on electricity demand and consumption of both commercial and residential buildings while the climatic impact on EC was analysed in [13] by Yau and Hasbi. Mideksa and Kallbekken in [14] analysed models and forecasted the impact of climatic variation on markets and electricity systems, while Yau and Hasbi presented the effect of a change in climate on commercial building and their technical services in the tropical regions [15]. The authors focused on the contributions of building toward climatic change and its effects on the structure of buildings, peak demands, and varying patterns of energy usage, emissions impact, thermal comfort, and building heating and building cooling requirements.

The aforementioned works successfully described a link between environment and EC during steady-state and transient-state conditions of indoor and outdoor surroundings. They further explained consumer (human) CL with varying environmental conditions but they fail to incorporate the effect of CBD in shaping energy profiles. Table 1 discusses some generic state-of-the-art works analysing the effects of environmental drifts on consumer CL and EC. A tick (✓) justifies the presence of characteristic for the mentioned referred paper and a cross (✗) represents that the mentioned characteristic is absent in referred paper.

In Table 2, the authors discussed an interrelation of environmental changes, consumer comfort, and EC. Taleghani [6] focused on outdoor thermal conditions and human comfort, further investigated the correlation between various latitudes and heat lessening schemes due to the variation of urban heat island phenomenon, and finally proposed the foliage as a superior choice for improving thermal comfort at the production level. Wang and Chen elaborated the impact of climatic change in EC and forecasting future weather data for 2020, 2050, and 2080 for 15-US cities addressing '2' types of domestic and '7' types of commercial buildings [31]. The author analysed that the effect of a change in climate fluctuated considerably amongst various kinds of buildings. Berger *et al.* discussed the impact of climatic change on EC and modelled regional climatic data applied to simulated thermal data from '9' existing office buildings [32]. The author found that heating demands were reduced slightly, whereas cooling demands increased significantly.

Moreover, the future effects of the urban heat island on electricity consumption of a modelled office building in London were predicted in [34] by Parish and Terrill. Dirks *et al.* [35] analysed real sectorial data (2009–2013) and analysed aggregate electricity demand in various Spain firms that was insensitive to temperature, while service sector firms possessed the highest sensitiveness. Climatic outdoor parameters influenced EC and production in the building, elaborated by Cruz *et al.* [4]. The authors used continuous real-time data from '4' high-performance research buildings and presented results from a set of correlations and regression analyses between several variables, namely: (a) outside temperature, (b) heat index, (c) electricity consumption, and (d) the production of solar energy, investigated that there was no influence of outside AT and humidity on EC and production. Furthermore, the relationship between EC and indoor environmental parameters was explained by Asadi *et al.* in [1]. Berger *et al.* in [5] applied aggregated data to a non-linear model to relate EC and temperature.

Although the aforementioned works discussed the effect of environmental changes on EC and consumer comfort, they lack to elaborate critically the detail investigation of consumer body relation to environment and EC. Moreover, they fail to analyse the effect of the environment over CBD leading to crests and troughs in ED.

The primary contributions of our paper in the light of above-stated issues are:

- These works highlight the consumer's EC with a change in environmental conditions. It also sheds light on various aspects on 'how the consumer's body receptors react to environmental changes that in-turn perturbs EC?'. High-ED can occur due to sudden climatic drifts for achieving consumer's thermal CL. Various state-of-the-art research works were discussed briefly in Section 1.
- We describe an effective consumer and surrounding mutual parametric interactions profoundly. The effects of a greener and healthier environment and its countless benefits are conferred.
- Moreover, environmental parameters such as (a) RH, (b) SI, (c) AT, and (d) CC are explained. The effects of the above-environmental parameters on CBD are also elaborated. The above effects on CBD are observed to maintain the desired consumer CL.
- Furthermore, our work investigates an inter-relationship between environmental parameters and CBD. The consumer body receptors react to change in climatic conditions resulting in ED. This relation also depends on CLo, consumer standard-of-living, and varying seasons.
- Finally, we present a conceptual closed-loop feedback EC model. This model is a complex non-linear adaptive system with the environment and surrounding parameters as input resulting in optimised EC considering consumer CL as a key parameter to the system. This claim is further supported by graphical analysis and technical investigation.

This paper is structured as follows: Section 2 illustrates effective consumer and surrounding interactions. Environment parameters relation with CBD is discussed in Section 3. Section 4 analyses mutual-relationship between environment and CBD. A closed-loop conceptual model is elaborated in Section 5. Section 6 concludes this paper with a summary and future work directions.

2 Effective consumer and surrounding interactions

The environmentalists and scientists around the globe with inter-governmental panel on climate change affirms that in the previous century the earth's land and atmosphere temperature raised to a mean value of ‘0.6°C’ (1.1°F) [33]. These environmental shifts put drastic impacts on climate of the earth, consequently causing sea level (SL) to rise, building up of ice in the Arctic sea, glaciers, and permafrost to melt, and last but not the least, the surface of the sea and huge lakes are becoming warm. In addition to the above, due to the decrease in the production of crops, the extreme droughts are increasing, ecosystem changes, and the weather is getting warmer and warmer affecting consumer health [33]. As the surrounding atmosphere changes, consumer lifestyles, living standards, and EC vary. Similarly, during energy production from fossil fuels, pollution from factories and industries, and disturbance in ecosystem from consumer inputs affects the surrounding atmosphere as well. Both consumers and surroundings have bi-directional impacts on each other. There are also some other very crucial inputs from consumers that severely affects the surrounding atmosphere such as the forests, air, CO_2 emission, CLo, and living standards.

2.1 Surrounding effect on consumer

Surrounding parameters directly affect the consumer's dynamics. The parameters affecting surroundings include (a) plantation, (b) location, (c) environment of the atmosphere, (d) seasons, (e) weather drifts, and (f) consumer's lifestyle. The dynamics of smart energy grid (SEG) consists of (a) energy markets, either wholesale or retail, (b) energy efficiency, **(c)** energy costs, **(d)** demand–supply management, **(e)** consumer empowerment, **(f)** incentive-based and time-based demand–response programmes, **(g)** optimised energy flows, and **(h)** economic development in SEG infrastructure. Surrounding parameters highly affects ED of SEG consumers. SEG is heading toward smart mega-energy grid with a basic aim toward green environment, and minimum emission of CO_2 to avoid global warming effects. In this perspective, both driving factors influence each other. For examples, dense plantation and forestry from consumers affect climatic drifts that in-turn perturb weather parameters, thus effecting EC. SEG consumers are affected in a similar fashion [36]. Similarly, extreme weather condition affects transmission-line efficiency, energy flows, generator performance, and EC of consumers. Green environment will shift consumers from pollution area to a healthier atmosphere region, thus increasing EC in one region.

2.2 Consumer influential effects on surroundings

Consumers impart a great effect on EC in various manners. Such effects are defined and explained briefly as:

- *Green house gases (GHG) emission:* The greenhouse effect is caused by GHG emissions through automobiles, industries,

Table 1 Summary of some generic state-of-the-art works on environment, CL, and EC mutual relations

Reference	En. C	E_C	HBIE	ED	CIP	COP	EMM	HMM	CCHC	CIEC	EHEC
[6]	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗
[1]	✓	✓	✗	✗	✓	✓	✗	✗	✓	✗	✗
[4]	✗	✓	✗	✓	✗	✓	✗	✗	✗	✓	✓
[7]	✗	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗
[16]	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
[8]	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗
[9]	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗
[17]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗
[10]	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
[18]	✓	✗	✓	✗	✓	✗	✗	✗	✓	✗	✗
[19]	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
[20]	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
[21]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
[22]	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
[23]	✓	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓
[24]	✓	✗	✓	✗	✗	✓	✗	✓	✓	✗	✗
[25]	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗
[26]	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗
[27]	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗
[11]	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗
[28]	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗
[9]	✓	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗
[12]	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗
[13]	✗	✓	✗	✓	✗	✗	✗	✗	✗	✓	✗
[14]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗
[15]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
[29]	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✗
[18]	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗
[30]	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
[24]	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗
proposed method	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓

Abbreviations: En. C: environmental change; EMM: environmental mathematical model; E_C: energy consumption; HBIE: human body interaction with environments; ED: energy demand; COP: climatic outdoor parameters; HMM: human body mathematical model; CCHC: climatic change and human comfort; CIEC: climatic impacts on EC; EHEC: effect of humidity on EC; CIP: climatic indoor parameters residential areas, and power plants. Such emissions are the reason behind global warming and climatic changes. The power demand forecasting system is disturbed due to the above changes [37].

- *Temperature variations:* Temperature variations are occurring due to global warming. Abrupt changes in temperature change the entire demand of electrical power [38].
- *Humidity:* In high humid conditions, air-conditioning load is increased. Even if the temperature is low, the power demand is still high [39].
- *Rain:* In summer, rain has a slight effect on EC but in winters, rain immensely increases the power demand. Rain in winters increases power loads as consumers mostly stay indoors and intensity of cold increases, resulting in high demand and stress on EC.
- *Forests:* In areas where the forestry is dense, the fluctuations in EC remain constant throughout the year. The areas with high deforestation result in abrupt changes in climate that leads to unpredictable EC [40].
- *SI:* SI has a direct relation with EC during summer. High SI results in high-ED. However, in winters SI has an inverse effect on EC.
- *Snow:* In snow areas, weather conditions are severe. In winters, temperature ranges below the freezing point result in high demand and EC.
- *Summer, spring, winters, and autumn seasons:* All the seasons have different EC patterns depending on consumer living standards and CLo.
- *Consumer psychology:*

  o *Decision-making models:* It depends on the decision making of the consumer such as: ‘how to’, ‘when to’, and ‘what-to-use’ for obtaining body CL.

  o *CLo:* Location plays a vital role in EC. Comparatively, in plain areas, power demand is high in summer than mountainous areas. In mountainous areas, winters are severe that leads to higher EC, compared with plain areas.

2.3 Consumer location

EC is highly dependent on CLo. The consumer EC changes with the change of their location [41]. The weather parameters such as wind speed (WS), air temperature (AT), relative humidity (RH), and solar irradiation (SI) vary from season-to-season and from location-to-location. On Earth, three major locations are identified as follows.

2.3.1 Mountainous region: The temperature difference between summer and winter of the mountains is very high. The altitude of the mountains is higher than the SL and plain areas; therefore, the consumer ED is variant. In winter, the temperature of the mountainous area becomes very low below the freezing point; therefore, more heating appliances are used, and the EC is at its peak. There is pleasant weather in summer on the mountainous area; therefore, the use of the cooling appliances is negligible, and as a result, the consumer ED is very low, compared with plain area and SL area.

2.3.2 Plain area region: In plain areas, there is a dramatic change in temperature during summer and winter, compared with SL and mountains. Plain area altitude is higher than SL and lower than mountainous area; therefore, the EC of the plain area is different

Table 2 Tabular analysis of related work

Study Author	Year	Focused area	Data characteristics	Findings
Taleghani [6]	2017	• outdoor thermal conditions and human comfort	• EC based on ‘320’ climatic conditions were studied, and comparisons were discussed • in this work, the impact of human thermal comfort in city open areas was examined • precisely, the analysis was converged on foliage in the form of roadside greenery, public parks, street green belts, greenery on rooftops, and green walls. Use of better reflective materials on rooftops and on the floors was the most generic approach to improve thermal comfort conditions in urban areas	• to improve the outdoor thermal CL in urban areas with highly reflective surfaces, vegetation, and various heat decreasing strategies were analysed • correlation was investigated between various latitudes and heat mitigation strategies due to the variation of the urban heat island phenomenon • it was investigated that foliage was a superiority to improvise thermal comfort at the pedestrian level
Jose *et al.* [33]	2015	• temperature impacts on firm's power demand were evaluated	• real, sectorial data (2009–2013) was extracted from firms	• aggregated electricity demand in Spain's firms was insensitive to temperature • sensitiveness varied across various sectors • service sector firms possessed the highest sensitiveness
Cruz *et al.* [4]	2017	• climatic outdoor parameters influence on EC and production in buildings were investigated	• this study uses continuous real-time data from ‘four’ high-performance research buildings and presented the results from a set of correlations and regression analyses between several variables, i.e. outside temperature, heat index, electricity consumption, and the production of solar energy	• found that there was no influence of outside AT on EC and production in the building • no correlation of humidity with electricity demand and consumption existed
Asadi *et al.* [1]	2017	• resident-based EC and IEQ was elaborated		• consumer interaction with EC in the building was discussed • IEQ was presented with acoustic comfort, indoor air quality, and chromatic CLs

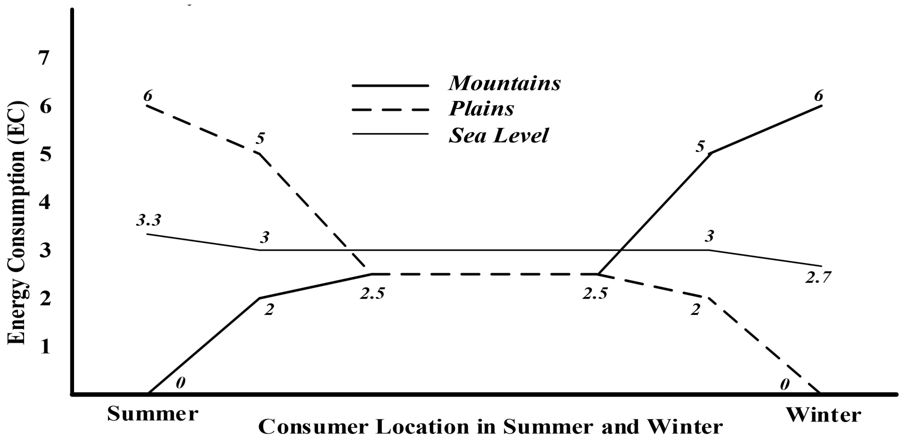


Fig. 1 *EC of consumers in summer and winter at three different locations [41]*

than the other two areas. In summer, the temperature is very high, and the consumers use more cooling appliances, compared with SL. In winter, the temperature of the plain area is not very low, compared with the mountainous area; therefore, heating appliances are not much utilised. During winters, EC on plain areas is very low, compared with SL and mountain.

2.3.3 SL region: In SL region, there is comparatively less change in temperature between summer and winter. The altitude of SL area is low, compared with the plain area and mountainous area. The average temperature difference between summer and winter is '∼10°C'; therefore, the EC is affected in summer and winter. In summer, when the humidity is high consumers feel warm, as a result, use more cooling appliances that result in increased EC. On the contrary, when WS is high, the consumer feels cool and switch off their cooling appliances that decrease their ED and vice versa.

2.3.4 EC for different CLos: The ECs of mountainous areas, plain area region, and SL region with respect to various seasons are shown in Fig. 1. It illustrates a graphical representation of the numerous effects of CLo on ED. Fig. 1 plots EC on the vertical *Y*-axis as a dependent variable, whereas on the *X*-axis two variables named 'summer' and 'winter' are plotted. For mountainous regions, the EC in Summer is low, while in winter this reaches its peak value. For the SL regions, the ECs for summer and winter remain on average. From Fig. 1, it is deduced that the EC for plains in summer is high because the consumer will run their air conditions, room cooler, refrigerators, and chillers.

3 Environmental parameters interaction with CBD

CBD are greatly affected by variation in environmental parameters. Environmental parameters such as RH, SI, dry bulb temperature (DBT), CC, acid rain (AR), wind speed (WS), DP, wet-bulb temperature (WBT), P, AT, AS, AP, and seasons are briefly explained in this section. Furthermore, classifications and their effects are also explained.

3.1 Relative humidity

Humidity is defined as 'the number of water vapours in the atmosphere'. RH is a ratio between the number of water vapours existing in the air to maximum water vapour the air holds at that temperature. The air is said to be saturated if RH is 100% [42]. RH effects EC pattern of consumers by affecting their body evaporation rate. RH is inversely related to the AT [3].

3.2 Solar irradiance

SI is defined as 'the measurement of electromagnetic rays after air scattering and absorption in the atmosphere or at Earth's surface'. The actual amount of solar radiation received from the sun varies with the angle of the sun and atmospheric conditions. The mean annual solar radiations received by the earth is '1725 kWh/m^2', out of which '31%' (that is, 537 kWh/m^2) is reflected into space and absorbed by the atmosphere. Solar radiation received by Earth surface is only '69%' (that is, 1188 kWh/m^2) [43]. The average daily solar radiation absorbed by the earth surface is '∼6 kWh/m^2' [44]. The SI increases or decreases the EC of the consumers depending on weather, climate, location, the season of the year, and numerous other environmental parameters.

3.3 Air temperature

The most commonly used weather parameter is 'AT'. The measurement of hotness and coldness of the air is called AT. Practically, all the weather parameters, namely: WS, RH, P, and evaporation rate depend on AT. When air is cool, it becomes denser and contracts. The dense air has a greater weight per volume compared with hot air. When high-pressure air moves into the area where the dense air is available, it mainly causes rain or storm. The sky will be sunny when low-pressure air enters the area, where the dense air is present. AT changes regularly and has a direct impact on EC. In winter, when AT is low, consumers consume more energy. When AT is high in winter, the consumers feel warm and switch off their heating appliances, causing a decrease in EC [45].

3.3.1 Dry bulb temperature: The amount of heat present in the air is determined by DBT. DBT and average kinetic energy of the air molecules are directly proportional to each other and express the capacity of heat present in the atmosphere. The ordinary thermometer is used to measure the values of DBT. In [46], it is illustrated that consumers feel warm and use more cooling appliances for cooling purpose when the DBT value is high. The consumers will consume less energy in summer by turning off their cooling appliances when DBT is low.

3.3.2 Wet-bulb temperature: WBT is a function of temperature and RH. It always lies in between DP and DBT. WBT is less than or equal to DBT. Lower values of WBT shows that air is capable of holding the large amount of water vapours, compared with the high values of WBT.

3.3.3 Cloud cover: CC means how abundantly sky is covered by clouds. CC is measured in the unit. CC is measured in the range of '0–9' Okta, where '0' means the sky is totally unclouded and clear, '8' refers to a completely clouded sky, and when the sky is obstructed from view, it means that the Okta is '9'.

3.3.4 Wind speed: When air is moving from region of high pressure to region of low pressure due to change in temperature, thus causing winds to flow. About '∼2%' of solar energy is reaching the earth surface; this is converted into wind energy (WE). The temperature of the earth surface increases and decreases unevenly, generating different atmospheric pressure zones that make air to flow from high to low atmospheric pressure zone. When the RH is low, it causes WS to decrease temperature and increase the evaporation rate, so the consumers feel cool. The consumers feel warm when RH is high, consequently, the temperature is high and WS is low.

3.3.5 Dew point: In the literature, DP is also called 'DP temperature (DPT)'. There is a direct relationship between DP and RH. When the temperature is high, then DP and RH are low and the evaporation rate is high. The consumer feels warmer than the normal days and uses more cooling appliances in summer, causing an increase in EC. The consumers feel cool in summers when DP and RH are high, and the evaporation rate is low, and thus uses less cooling appliances.

3.3.6 Precipitation: P effect is caused when heat from the sun starts evaporating water from the surface of the earth. Water will continue to evaporate until the local atmosphere reaches its saturation point. The evaporation also depends on AT of the atmosphere. The warm air can hold more water vapours, compared with cold air. The P is produced only if the evaporated water condenses. Rain, snow, freezing rain, sleet, and hail are the various forms of P. Every form of P depends on the change in AT with altitude [47].

Table 3 presents a mutual relation of the environment with surrounding parameters. The increase or decrease of one parameter affects the intensity of the other parameter. Table 3 statistics may vary from 'region-to-region' and 'climate-to-climate'. Table 4 describes the effect on EC with varying CL of the consumer with drifting DBT. Time dependency is the major factor involved in the CL of the consumer.

When consumer is moving from outside transient environmental state to an indoor environment, time will be required for CBD to settle down to the existing indoor environment. CL of the consumer will vary with DBT variation, for example, in neutral environment temperature, the consumer will be comfortable with a previous existing comfortable temperature. Similarly, consumer movement in a very hot environment will perturb CBD drastically. Thus, brain thermostat will force the consumer to move toward a comfortable zone. Similarly, relationships without CL and EC are analysed by authors in [36].

4 Inter-relationship between environment and CBD (C_{bd})

The relationship of environment parameters (ε_i) with CBD (C_{bd}) is of great interest. The environmental parameters, directly and indirectly, affect the body dynamics of the consumer resulting in an EC to vary. For consumer achieving a $C_{f,opt}$, this relationship is also dependent on location, consumer activity, and living standards as well. For example, a consumer living in a snowy mountain region will feel comfortable in winter season of a city without need of much heating in that place. Similarly, a consumer living in the African plain area will feel much comfortable in summer season of Europe without the need of air conditioning. The environment impact on C_{bd} directly affects the peak EC (E_C). The environmental parameters affecting C_{bd} and their inter-relationship are briefly explained in this section.

4.1 Consumer heat exchange relationship with environment parameters

The consumer is a living organism that obeys 'second-law of thermodynamics'. Consumer exchange body heat with the surrounding environment (whether indoor or outdoor) and environment exchange heat with consumer body (C_b). Assume q_c as body heat exchange rate with the environment, T_a as AT, T_b as body surface temperature, and h_c as the coefficient of convection. The mutual heat exchange is described as $q_c = h_c\ (T_b - T_a)$. This shows that q_c, a linear relationship between two quantities. Moreover, short-wave radiation model is described as $q_{sw} = \alpha_b f_s I_s$, where α_b is absorptivity of the consumer body surface, I_s is an incident short-wave parameter, and f_s is the projected area factor of consumer body [31]. On the basis of Fiala model, dynamic thermal sensation model shows those body dynamics varies with steady and transient-state responses of the environment. Moreover, we

Table 3 Environment and surrounding mutual effects

		Surrounding parameters						
		CO_2 (inc)	Forestry (inc)	CLo			CO_2, dec	Forestry, dec
				M	SL	P		
environmental parameters	DBT	Inc	Dec	Dec	Inc	Inc	Dec	Inc
	RH	NE	Inc	Inc	Inc	Dec	NE	Dec
	SI	NE	Dec	Dec	Inc	Inc	NE	Inc
	CC	NE	Inc	Inc	NE	Dec	NE	Dec
	AR	Inc	Inc	Inc	NE	Dec	Dec	Dec
	WS	NE	Dec	Inc	Inc	NE	NE	Dec
	DPT	Dec	Inc	Inc	Inc	Inc	Inc	Inc
	PP	NE	Inc	Inc	Dec	Dec	NE	Dec
	AT	Inc	Dec	Dec	Dec	Inc	Dec	Inc
	WBT	NE	Inc	Inc	Inc	Dec	NE	Dec

Abbreviations: CO_2: carbon dioxide; SL: sea level; DBT: dry bulb temperature; SI: solar irradiance; AR: acid rain; DPT: dew point temperature; AT: air temperature; Inc: increases; NE: no effect; M: mountainous; P: plain; CC: cloud cover; PP: precipitation; RH: relative humidity; WS: wind speed; WBT: wet-bulb temperature, and, Dec: decreases.

Table 4 Inter-relationship between CL, EC, and environmental parameters

Environment parameters	Variation	Thermal sensation	Indices	CL	EC
DBT	much increased	very hot	4	minimum	maximum
	increased	hot	3	minimum	maximum
	medium increased	warm	2	deviates	increased
	slightly increased	slightly warm	1	slight deviation	slightly increased
	no change	no change	0	acceptable	minimum
	much decreased	slightly cool	−1	slightly deviate	slightly increase
	decreased	cool	−2	deviate	increase
	medium decreased	cold	−3	minimum	maximum
	slight decreased	very cold	−4	minimum	maximum

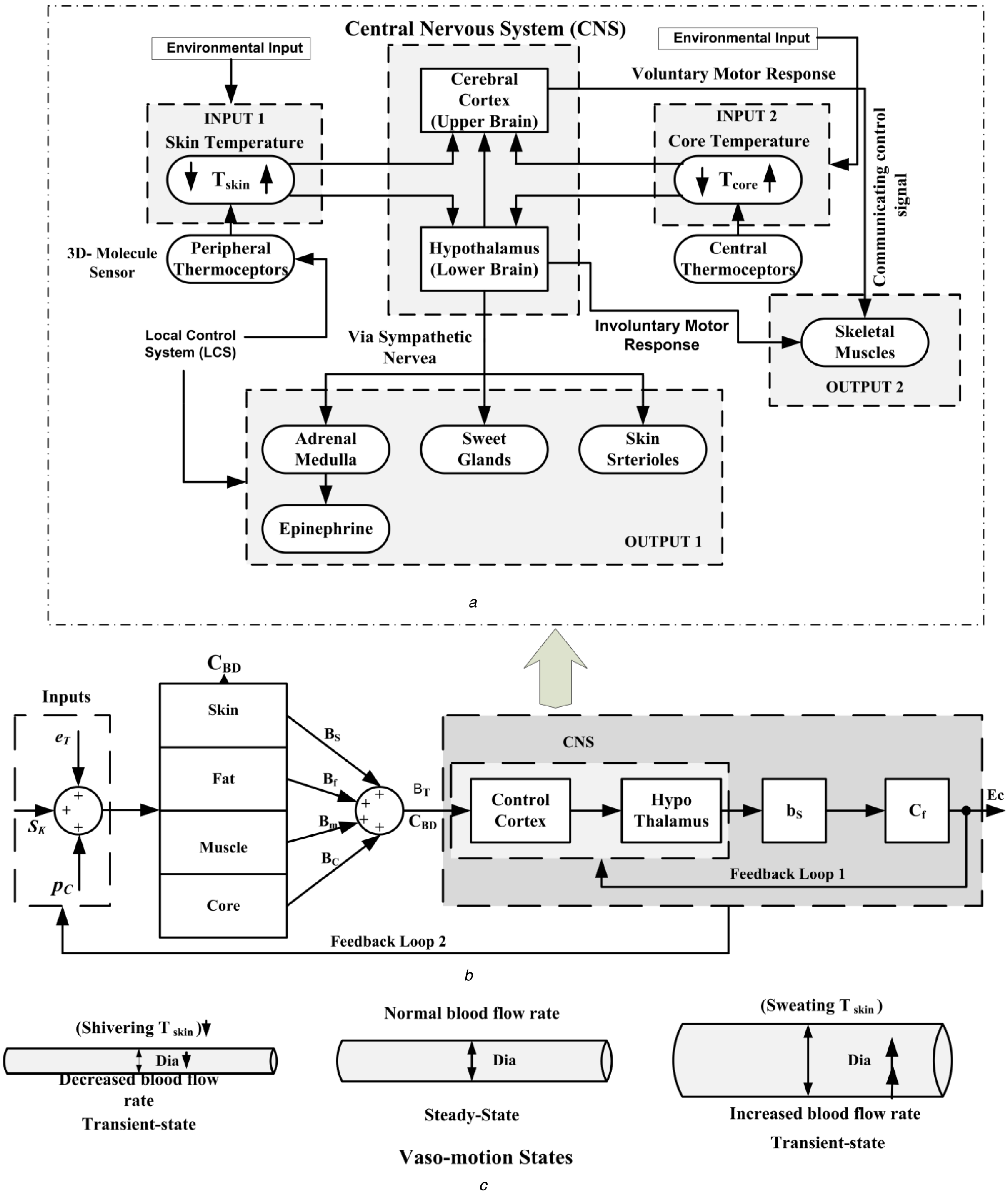


Fig. 2 *Variations in consumer body with environmental inputs*
(a) Central control system and local control system of consumer body, ***(b)*** Closed-loop feedback system of consumer body and environmental inputs, ***(c)*** Vasomotion action during transient and steady states

considered a dynamic model that incorporates: (a) core, (b) skin, (c) fat, and (d) muscle layers of consumer presented in [24].

4.2 CBD (C_{bd})

Consumers (humans) are the class of living organisms that present homoeothermic response. They exchange energy with their surrounding environment. Owing to the above promising feature, consumers maintain a fairly constant internal body temperature with varying environmental parameters. The constant internal body temperature range is ‘37 ± 1°C’ or ‘98.6 ± 1.8°F’ [9]. Hyperthermia and hypothermia are the conditions of the CNS when body standard temperature increases or decreases this threshold (~ ±2°C). For consumer body comfort, homo-thermic steady state is vital. To maintain the above-stated thermoreceptors located on various body parts exchange heat stress signals with hypothalamus of the brain. Fig. 2*a* explains ‘central control system’ (CNS) and local control system (thermoreceptors) coordinating via voluntary and involuntary motor responses to maintain an optimised CL ($C_{f,opt}$) [48]. Skin temperature (T_{skin}) and core temperature (T_{core}) are the inputs from external environment penetration, while output signals are generated by the central system of the brain. Fig. 2*a* further describes the variational effects of skin temperature. For example, when T_{skin} increases in the environment, radiant heat is absorbed from relative surroundings. Moreover, heat absorbed by C_b is transferred to colder body parts through deep tissues. Furthermore, heat loss takes place from respiratory passages and body skin.

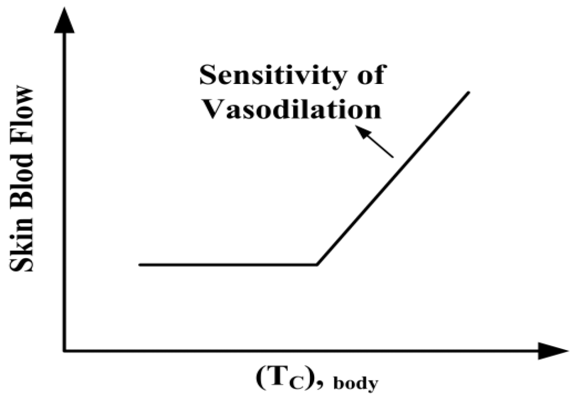


Fig. 3 *Relation of body temperature and skin-blood flow [46]*

Fig. 2*b* shows a closed-loop feedback system of C_b with stochastic environmental inputs. The heat balance system of Earth is defined as $m_e C_e \dot{T}_e = \dot{q}_s - \dot{q}_e + \dot{q}_{ins}$,, where T_e is the average temperature of the earth, m_e is the mass of Earth, C_e is the average heat capacity, q_s is the heat intake from the sun, q_e is the heat radiations from Earth surface, and q_{ins} is the heat converted to Earth planet. Earth's temperature and environmental parameters are affected by differential parameters $\dot{q}_s$, $\dot{q}_{ins}$, and $\dot{q}_e$. Environmental input, surrounding input, and consumer psychology input disturb steady-state blood flow of consumer body. The blood will flow inside four 'four' layers, namely: (a) skin, (b) fat, (c) muscle, and (d) core. Transient blood flow from the above four sections affects C_{bd} that in return stimulates central cortex (upper-brain section) and hypothalamus (lower-brain section). Finally, BSs b_s will force the consumer to maintain an optimum CL C_f. Feedback-loop 1 and Feedback-loop 2 are the signals exchanged with the C_b and input section, as depicted in Fig. 2*b*.

Fig. 2*c* illustrates steady and transient vasomotion states of consumer body. Blood-flow rate inside the body vessels will be normal during steady state. Transient blood state is the result of T_{skin} variation. When T_{skin} increases, blood-flow rate will increase, vasodilation occurs with increased diameter (dia-'d') of the blood vessel. This will result in sweating (heat loss) to maintain an optimum blood-flow rate. Vasoconstriction will occur when T_{skin} decreases and C_b will shiver. Brain thermostat detects the drift in body temperature from normal operational range (37 ± 1°C) or (98.6 ± 1.8°F). Vasomotion $V_m(t)$ is described as

$$V_m(t) = V_m(t)_{steady} + V_m(t)_{dynamic} \tag{1}$$

$$V_m(t) = \begin{cases} V_m(t)_{steady}, & \dot{T}_{skin} = 0 \text{ and } \dot{T}_{core} \\ V_m(t)_{dynamic}, & \dot{T} = 0 \text{ and } \dot{T}_{core} \end{cases} \tag{2}$$

For more clarity, $(T_c)_{,\ body}$ is optimised consumer body temperature, body heat dissipation and heat conservation are analysed as

$$(T_c)_{body} = \begin{cases} \dfrac{d(T_c)_{body}}{dt} > 0 \\ \dfrac{d(T_c)_{body}}{dt} < 0 \end{cases} \tag{3}$$

From (2) and (3)(T_{skin} and T_{core}) are functions of $(T_c)_{body}$. Furthermore, from (3), $(\dot{T}_C)_{body} < 0$ will cause vasodilation and $(\dot{T}_C)_{body} < 0$ will result in vasoconstriction.

The effect of consumer body temperature on the skin-blood flow is examined from Fig. 3.

4.3 Effect of environment on C_{bd}

The C_{bd} parameter is mostly affected by the indoor and outdoor environments. All environment parameters are mutually related and vary with respect to change occurring within each other. The rise in RH increases temperature or DBT, resulting in a change in C_{bd} that in response disturbs the consumer CL (C_f). To achieve the maximum CL (C_{f}, max), the consumer will use cooling appliances resulting in more E_C. Moreover, DBT also effects RH and DP temperature T_d as

$$T = \frac{1}{5}(100 - \text{RH} + 5T_d) \tag{4}$$

Equation (4) clarifies inter-dependency of environment parameters. Considering (4), DBT directly perturbs T_d and RH.

To this end, we conclude our major discussion as:

- Environment and surrounding affect consumer living standards.
- Consumer prefer a comfortable environment zone justified through thermostat brain sensational signals.
- External environment varies C_{bd} and consumer moves toward $C_{f,\ max}$ zone through switching ON/OFF of cooling or heating devices.
- $C_{f\,max} = f(\epsilon_i, C_{bd}, b_s)$ and $E_c = f(\epsilon_i, C_{bd}, b_s, C_f)$. For strengthening our last two remarks, we move on to a new conceptual model of E_C. This is presented in the next section.

5 Moving the literature forward: closed-loop EC model – a concept

Whether in the design of energy buildings for the cold or hot environment or vehicles design for consumer comfort, consumer psychology plays a pivotal role in shaping energy profiles for SEG policymakers. Consumer psychology is affected by neighbouring surroundings and environment. The stability of consumer body parameters deteriorates as environmental parameters shifts from the comfort zone. Consumer body variations (thermoreceptors response from various body parts) activate CNS of the brain (thermostat). Brain signal compels the consumer to retain comfort to an optimum point ($C_{f,opt}$). The consumer will perform various activities to fulfil body needs depending on the environment. For example, in winter season due to a reduction in body core temperature from '37°C', the consumer will either 'switch ON' or increase the heating of building (or room) through a regulator (thermostat controller). Owing to this action, the EC of the consumer will vary. Fig. 4 presents the block diagram of our system model.

5.1 Working principle

The parameter E_C is a function of CBD C_{bd}, environment ε_i, and consumer CL C_f, defined as 'E_C' described in Fig. 5. Fig. 5 illustrates a closed-loop feedback control system of consumer E_C. The environment parameter $\mathcal{E}_i$, where $i = \{1, 2, 3, \ldots, n\}$ and consumer psychology ρ_C are the major inputs to the consumer body C_b. The variable ε_i depends on CLo, whether inside room (or building) or outside environment. The ε_i parameter intensity and effectiveness are a dependent quantity affected by consumer surrounding and location. The factor ρ_C is highly stochastic and probabilistic dependent on consumer activity and clothing. The consumer may perform normal activity such as office work and home sleep. The exertion activity, namely exercise is a transient state in C_b, while normal activity causes steady-state operations in C_b. Consumer clothing (C_{cl}) provides a barrier to $\mathcal{E}_i$. C_b is affected by $\sum_{i=1}^{n} \varepsilon_i$ and ρ_C inputs thus perturb C_{bd}.

C_b is a complex structure, as demonstrated in Section 4. We considered multi-node Stolwijk's model with '16' body segments, namely head, chest, back, left hand, right hand, left leg, right leg, pelvis, left shoulder, right shoulder, left foot, right foot, left thigh,

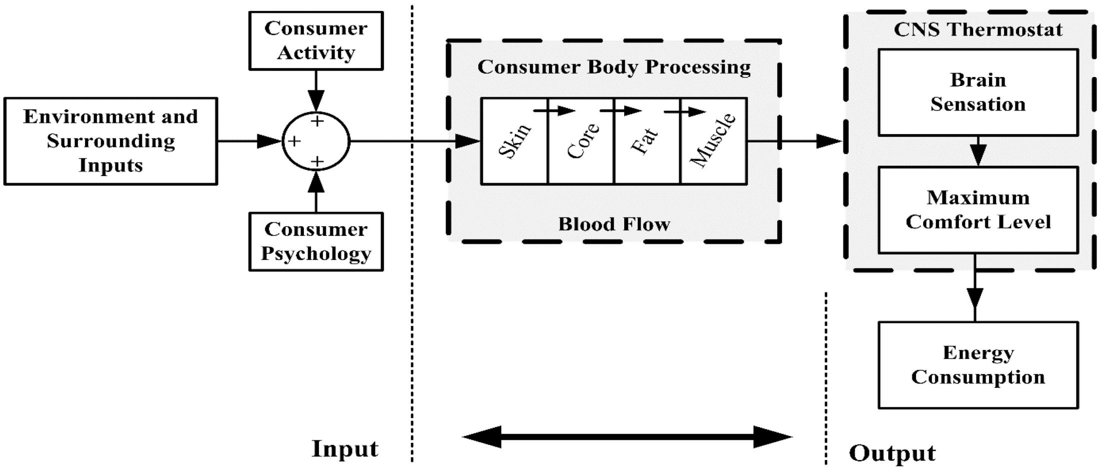


Fig. 4 *System block diagram*

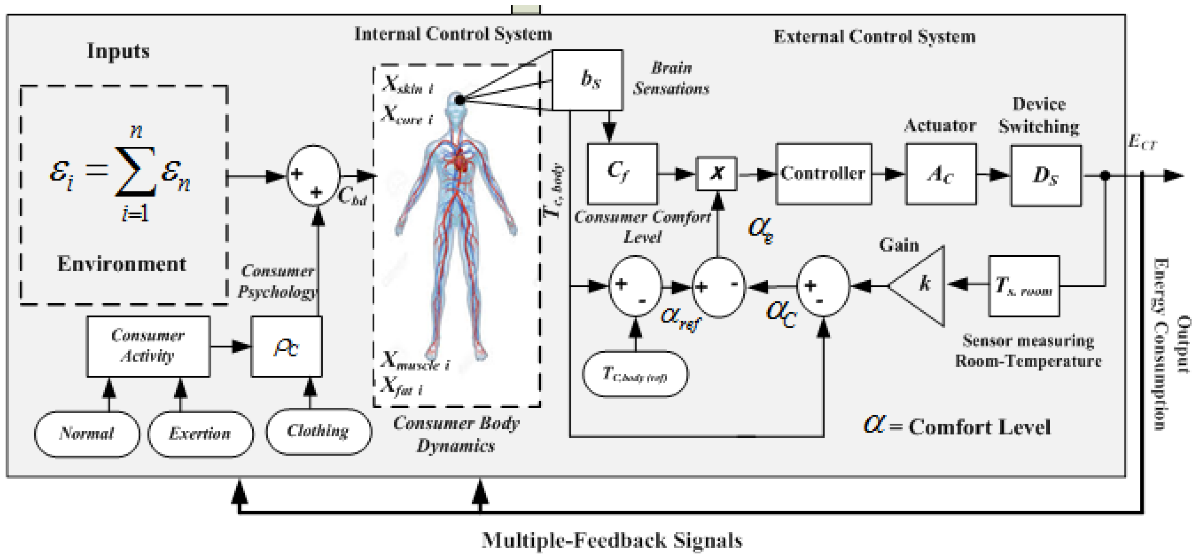


Fig. 5 *Closed-loop feedback system of E_C model*

and right thigh. The individual C_b segment comprises of 'four' main layers that are: (a) skin, (b) core, (c) fat, and (d) muscle. In this paper, consumer blood temperature C_{bt} and skin temperature T_{skin} are considered for consumer thalamus operations in stable and unstable environments. In medical literature, hypothalamus regulation $h_r(t)$ is controlled by C_{bt} and T_{skin}. Owing to C_{bd} and $h_r(t)$, three thermos-responses are noteworthy, namely: (a) vasomotor (b) sudomotor, and (c) metabolic. The instability caused by ε_i and ρ_C is reflected in '16' body parts with '4' individual body segments, thus perturbing consumer blood dynamics. BSs b_s are activated through various thermos-receptors of C_b. Owing to this response, the consumer will maintain optimum CL $C_{f,opt}$. At $C_{f,opt}$, the consumer will feel comfortable and satisfied. Above or below $C_{f,opt}$ threshold, instability in C_b will result. For maintaining $C_{f,\,opt}$, the consumer will 'switch ON' (heating/cooling) electric devices, causing E_C to rise.

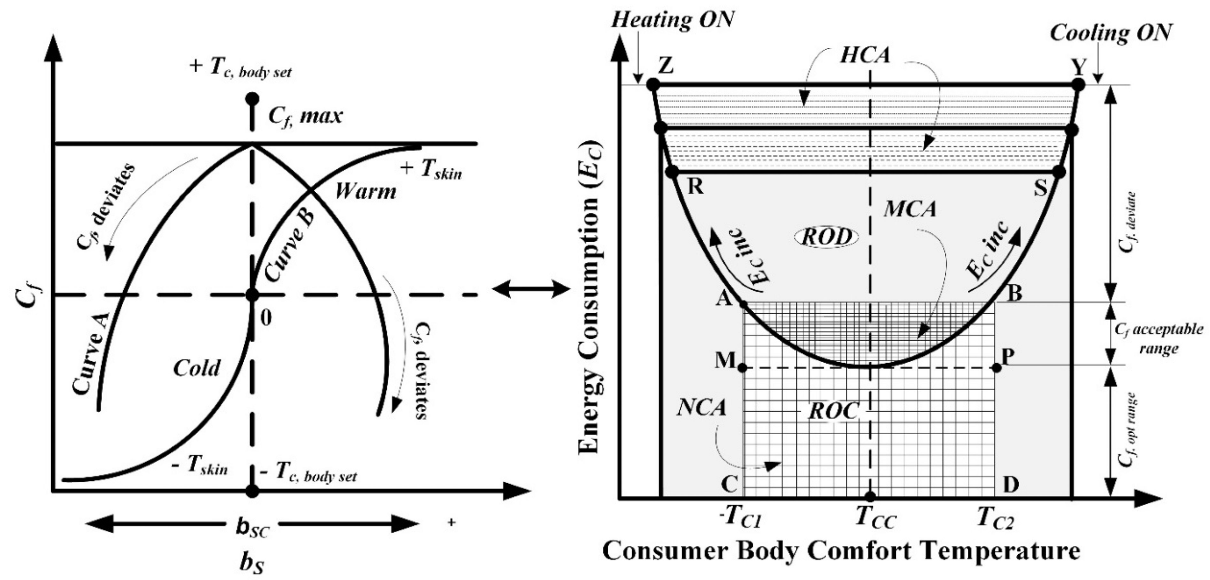
The demanding task is to maintain C_f at an optimum point with $C_{f,max}$. We introduced a controlling factor α_e, a difference between actual comfortable body threshold α_c and consumer body reference α_{ref}. α_{ref} is the difference between actual comfortable body temperature $T_{c,body}$ and a reference $T_{c,body(ref)}$. The comfortable threshold α_c is calculated by gain factor K, a ratio of $T_{c,body}$, and comfortable room temperature $T_{s,room}$ calculated from a room sensor. Difference between $(T_{c,body})_{actual}$ and $(T_{c,body})_{calculated}$ is α_c. The factor α_e C_f is input to proportional–integral–differential (PID) controller. The error signal α_e C_f generated through feedback of PID is further synthesised by PID gains (K_p, K_i, K_D). The output is a control signal that triggers an actuator. Finally, through an optimal range of desired C_f, switching devices will result in E_C of the consumer. The desired E_C function is described as $E_{cT} = E_N + \alpha_{Cf}$. When α_e is zero, C_b is in normal or steady-state mode, $E_{CT} = E_{CN}$ when α_e varies, E_{CT} will drift to a new value.

5.2 Parameters C_f, b_S, and E_C mutual interpretations

The plot of C_f with respect to b_s is described in Fig. 6*a*. This plot is a generic curve, a logistic asymmetrical function as shown in curve A. At one definite point of b_s, called a 'critical consumer BS point b_{sc}', the value of C_f will be maximum. This function is asymmetrical because various body parts responses to environmental drifts are variable. Curve B describes a relation between body skin temperature T_{skin} and b_s. As T_{skin} increases, C_b gets warm and vice versa. With T_{skin} increases, b_s will increase on the positive side. This curve is steeper for the warm side and gradual response for the cold side, thus presenting a dynamic b_s model. Total b_s response is described as

$$b_s(t)_T = b_s(t)_{steady} + b_s(t)_{dynamics} \tag{5}$$

$$b_s(t) = \begin{cases} b_s(t)_{steady}, & \dfrac{d}{dt}(T_{skin}) = 0 \text{ and } \dfrac{d}{dt}(T_{core}) = 0 \\ b_s(t)_{dynamic}, & \left(\dfrac{d}{dt}(T_{skin}) \text{ and } \dfrac{d}{dt}(T_{core})\right) > 0 \end{cases} \tag{6}$$



a *b*

Fig. 6 *Parameters C_f, b_S, and E_C mutual interpretations with*
(a) Skin temperature variations symmetrically and asymmetrically, ***(b)*** Consumer C_f variations with E_C

C_b will be in the steady-state mode when there is no increase in T_{skin} and T_{core}. With sudden environmental drifts, C_b will shift toward dynamic mode. For curve A, with $C_f = f(b_s)$, we conclude that C_f is a piece-wise linear behaviour of consumer b_s. Moreover, with the variation of various consumers body parts responses and variation from the consumer-to-consumer, the above function is asymmetrical. Furthermore, considering some major C_b responses, this function is symmetrical as well. Now analysing C_f response with respect to consumer comfortable body temperature T_{cc} and E_C critically in Fig. 6*b*. This curve describes the non-linear behaviour of *E*c with comfortable body temperature *T*c. *E*c increases in switching heating and cooling devices. The region CMPD shows NCA ‘no consumption area’, while MCA is ‘minimum consumption area’.

MCA also describes an acceptable range of C_f. ‘Region-of-optimum comfort’ is shown by CMPD as $C_{f,opt}$.

This region is ‘region of convergence’. RZYS shows ‘high consumption area’. As the value of $C_{f,opt}$ deviates from the set point, E_C increases drastically, describing a divergent response in E_C. The region of divergence is shown by AZYB. In this model, E_C operates as

$$E_c = \left\{ \begin{matrix} E_{c\max},\ T_{CC}\langle T_{C1} \text{ or } T_{CC} \rangle T_{C2} \\ E_{c\min},\ T_{C1} < T_{CC} < T_{C2} \end{matrix} \right\} \tag{7}$$

5.3 Technical analysis

Consumer thermal comfort for indoor and outdoor spaces is directly associated with social-living standards of various consumers residing in either rural or urban region. Consumer response to environmental shifts with hot, cold, and mild conditions perturbs C_f. The outdoor environment is more rapidly changing C_{bd}, compared with indoor environment parameters. Thus, the E_C effect will be more for outside spaces. Moreover, the thermal history of the subjects (consumers) will play a pivotal role in shaping E_C data. Furthermore, among various driving forces for perturbing C_{bd}, T_{skin} is more common psychological parameter affecting this change. T_{skin} is more affected by the radiational temperature of the environment. Researchers and scientists declared T_{skin} as a more effecting controlling parameter for studying C_{bd}, compared with RH and DPT. The disturbance in C_{bd} varies with the clothed and unclothed consumers. Environment parameter effect E_C in a way ‘how consumer reacts to ‘short-run’ and ‘long-run’ weather shocks’? Intensive (short-run) and extensive (long-run) margins influence consumers adaptability, ‘short-time’ hot days and cold days will drive E_C differently, compared with ‘long-span’ hot days and cold days. However, with extensive margins, consumer's adaptability, consumer decisions, consumer appliances purchase, and shift toward a comfortable environment is entirely different.

Thus, energy costs associated with climatic drifts will inevitably depend on future consumer financial status and next generations’ technologies. Policymakers of SEG plan for weather-driven-energy-costs to increase consumer empowerment and consumer satisfaction (comfort) by offering different price plans.

There are some interesting caveats to consider for the above model. They are described as:

- E_C patterns and price-plan fluctuate with climatic drifts.
- The change of living style from one climate to other will involve energy costs. For unexpected climatic shift, this transition may result in sub-optimal reversible investments. Thus, the transition will favour consumers for extensive margins.
- Consumers will re-locate indoor (household) appliances accordingly with climatic shifts.

Consumer energy interactions analysed by SEG monitoring and measurement system will be more effective by incorporating: (a) appliances re-formation with bi-directional interface of consumer body and indoor environment, considering CL on highest priority, (b) building designs for C_{bd}, C_f, and E_C mutual interactions, and **(c)** consumer on-demand resources through advanced metering infrastructure.

5.4 Concluding remarks

Promising features evaluated from this new model are described as:

- Environmental patterns effecting C_{bd} describe more spatiotemporal heterogeneity toward consumer ED.
- Consumer behaviour (psychology) toward optimum is predicted from T_{skin}, ε_i, and C_{bd}.
- The model is showing amorphous environmental variations resulting in chaotic-dynamical response in a consumer body.
- The closed-loop feedback system is non-linear complex and hierarchical structure showing high sensitivity to perturbations.
- Moreover, this system is ‘complex adaptive’ with various promising features such as inter-dependencies between

component elements, co-evaluation, robustness, optimal connectivity, and iteration and requisite variety.

- Furthermore, the above model is a thermodynamic open and non-isolated system that can be modelled using a set of complex multi-non-linear differential and stochastic equations.
- With enhanced consumer empowerment and consumer input, the average E_C rate will be further optimised. Thus, through consumer socio-economic dynamics such as affordability, employment status, locality, and past E_C history may increase the economic growth of the country.

6 Conclusion and future work

Modelling, design, and analysis of complex EC models based on consumer and environment inputs are challenging tasks. The stochastic behaviour of consumer leads toward uncertain energy patterns. The foremost entity behind probabilistic behaviour is internal body dynamics that affect BSs. Considering the above factors, consumer psychology, living standards, and activity levels are the major contributing factors toward EC. These factors depend on various environmental parameters that perturb steady CBD. The BSs are then activated that forces consumer toward an optimised level of comfort. This CL is achieved through critical body temperature that is affected by surrounding and environment parameters such as temperature, RH, and P. Moreover, depending on the location of the consumer, whether inside the building or open environment or at mountainous, plains, and SL, EC varies. Furthermore, the EC of the consumer is directed by BSs. To predict and forecast the EC model, complete set of varying parameters are vital for analysis.

In near future, we will work on the following domains of EC model described as:

- We will mathematically model this system with a non-linear differential set of equations that will include all parameters from input to output.
- On the basis of the above model, our work will provide convergence and divergence proofs from literature for validating this claim.
- Moreover, this model will be analysed using stochastic blood equations and probabilistic environmental inputs.
- Furthermore, statistical tests will be performed from the literature to further support our claim.
- Finally, exemplary cases will be considered in each scenario to compare simulation results with actual calculations.

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